# Lightweight Primary Mirror for NGST Using a Thin Glass Facesheet With Active Rigid Support

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# NGST primary mirror requires a break from conventional technologies

| | HST | NGST |
|---|---|---|
| Collecting area | 4.5 $m^2$ | 25-40 $m^2$ |
| Weight/area | 180 $kg/m^2$ | 15 $kg/m^2$ |
| Operating temperature | Warm | 40 K |
| Focal ratio | F/2.4 | F/1.2 |

Cost must be held down

Optical quality figure and smoothness must be achieved

# Minimize weight using an active mirror

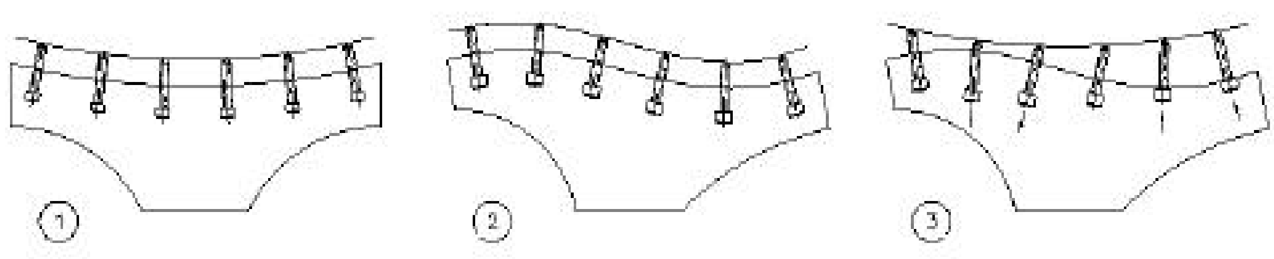
Achieve accurate figure with low-mass system by using a mirror with closed-loop control

2 mm thick glass facesheet provides smooth, stable optical surface

Lightweight composite structure provides rigidity

Actuators connect the glass to the support structure and compensate for its distortions

Loop closed using wavefront sensor and computer




Undistorted mirror

Support distorts, taking membrane with it

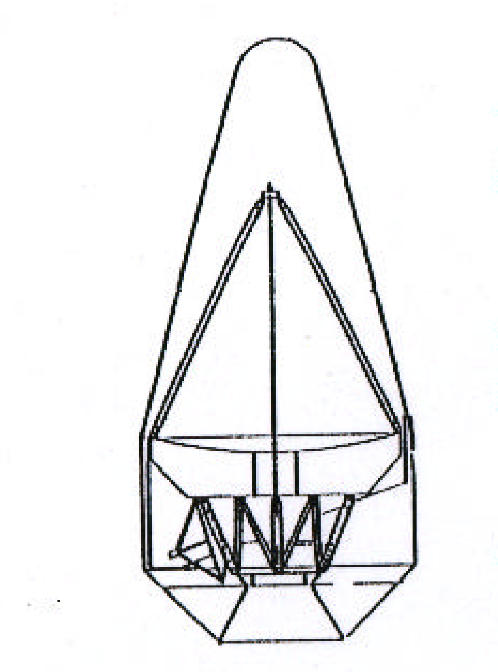
After wavefront error is measured, actuators adjust length to return membrane to undistorted shape

# Special features required for the flight mirror

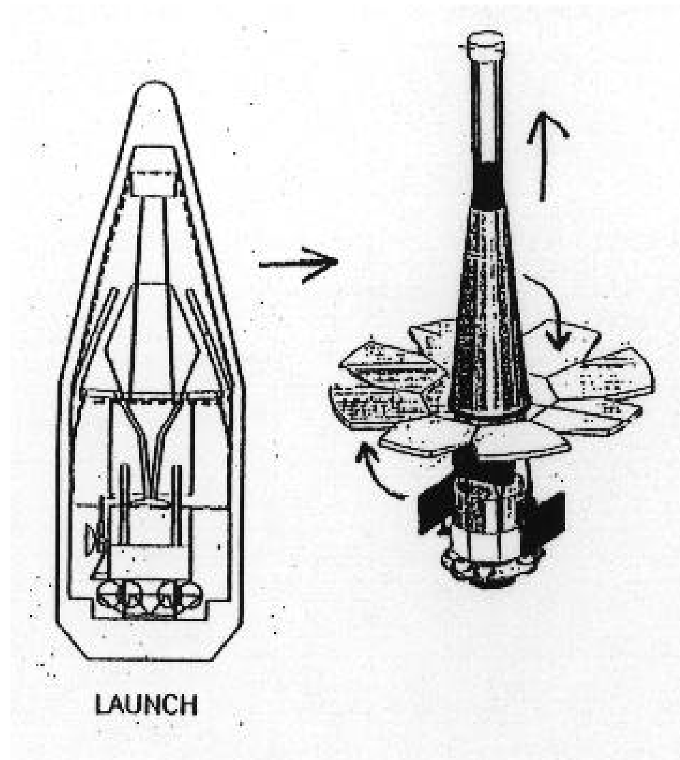
- Heat transfer from the back of the mirror.  The highly reflective front surface will lack emissivity required for passive cooling.
- Actuators must be retractable.  If an actuator fails in any way possible, it will be retracted and removed from the system.  The actuator density is sufficient that several actuators could be removed without significantly  affecting the figure.
- The hardware must survive the launch load.  We demonstrated the ability of the shell to survive when it is constrained to rigid actuators.  The flight hardware will not be able to support the shell during launch.    One idea is to fully retract the membrane against an edge seal and “suck” the part into soft bumpers.

# Mirror configuration

This active mirror concept is equally valid and valuable for a monolithic primary as a segmented deployed primary



Assembled 6-m monolith




Deployed 8-m concept

# Monolithic mirror vs segmented mirror

The monolithic system is stiffer, lighter, and cheaper

Both rely on active control to maintain their optical figure

Costs of optical fabrication are similar

Monolith requires investment in launch shroud

Deployable requires investment in deployment and alignment systems

A fully assembled telescope with monolithic primary can be tested on the ground, minimizing risk to the program

The segmented mirror requires edge matching which complicates the system

The monolith is limited to 6 m, segmented is limited only by imagination

# State of technology for MARS mirrors

## (Membrane with Active Rigid Support)

System concept

- Demonstrated at 53 cm

Rigid support structure

- Uses mature composite technology

Manufacture and launch of membrane

- Glass mirrors up to 8-m and f/1.25 are now cast and polished
- 2-mm thick glass membranes demonstrated up to 53-cm
- 2-mm thick, 1-m diameter membrane survived launch test

Actuators

- Early prototype actuators achieve 25 nm resolution at 77K

Closed loop wavefront correction

- Adaptive optics programs are mature with 100 Hz bandwidths

# Support structure

Use ***existing technology base*** of lightweight composite structures

Structures made from sheets of carbon fiber/epoxy laminate to achieve excellent stiffness to weight ratio, at < 5 $kg/m^2$ for structures up to 6 meters in diameter

Shape changes in the composite structure will be compensated with the closed loop control system.   Shape changes will be caused by

- material instability
- 270 deg temperature drop
- thermal variations within the structure
-
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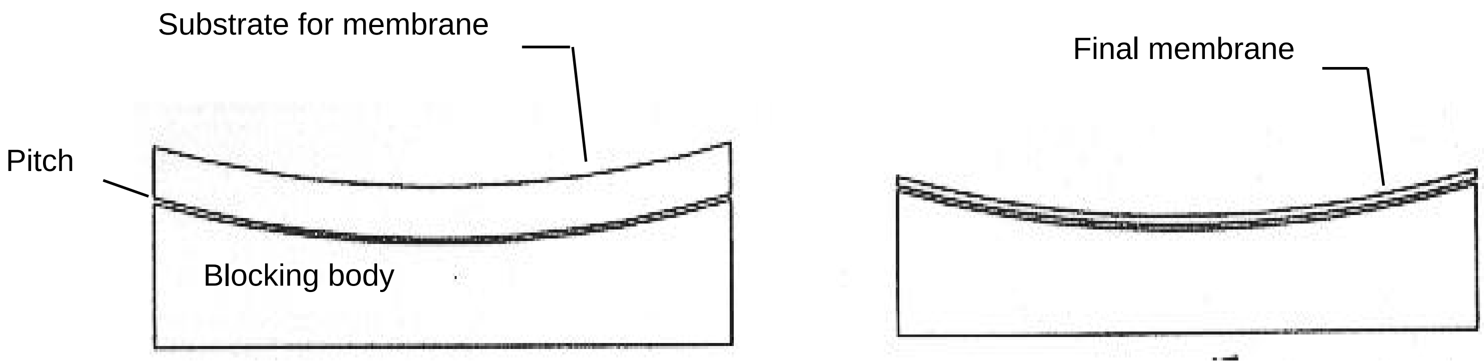
# Thin shell fabrication

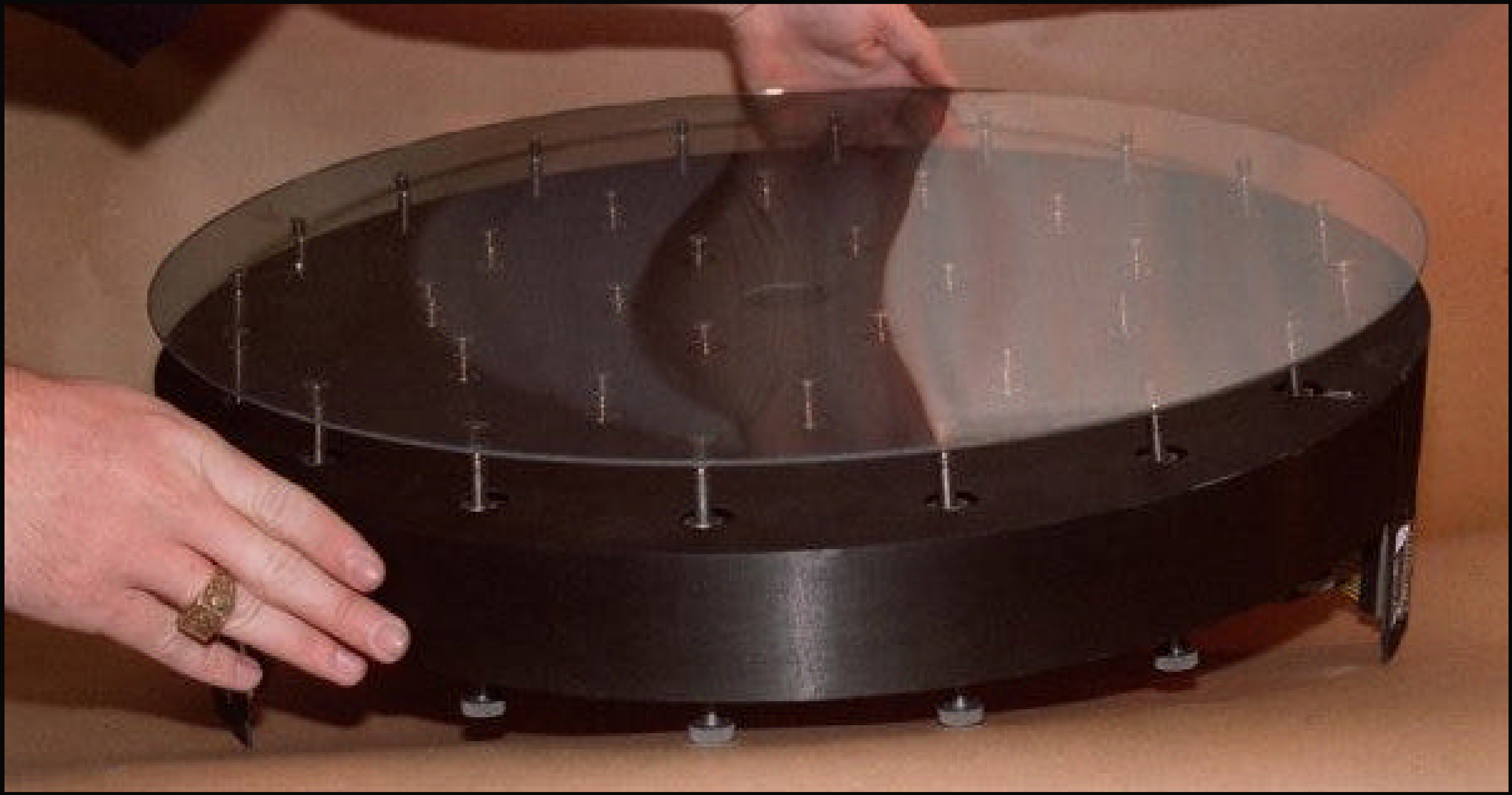
The concept is to work the glass while it is rigidly bonded in place

**<u>Sequence of operations for manufacturing concave glass membranes</u>**

- Generate and polish concave sphere into rigid blocking body
- Generate and polish convex sphere on back of relatively thick meniscus
- Attach the meniscus to the blocking body with pitch
- Generate membrane to near final thickness
- Grind and polish membrane to specified figure
- Warm to melt pitch, slide membrane off blocking body



# Demonstration of a 53-cm prototype

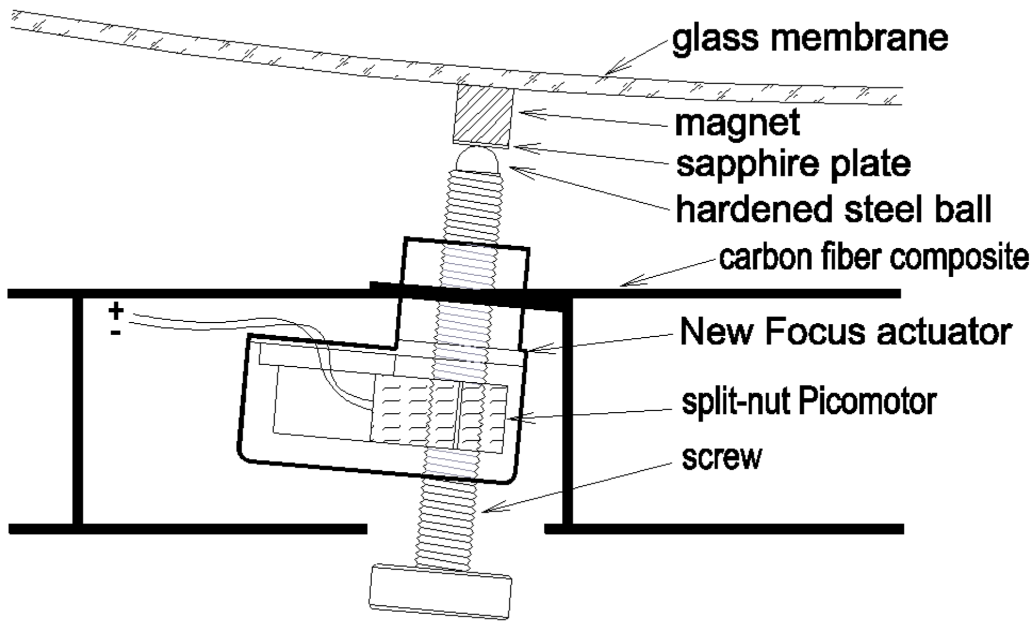


2 mm thick Zerodur membrane, f/1.4 sphere
Carbon fiber support made by Composite Optics, Inc
36 screw-type Picomotor actuators from New Focus
Total mass of 4.7 kg (21 kg/m$^2$)
Figure 33 nm rms after backing out static gravity effects
Substrate and some funding provided by NASA Marshall

# Actuators for 53-cm prototype

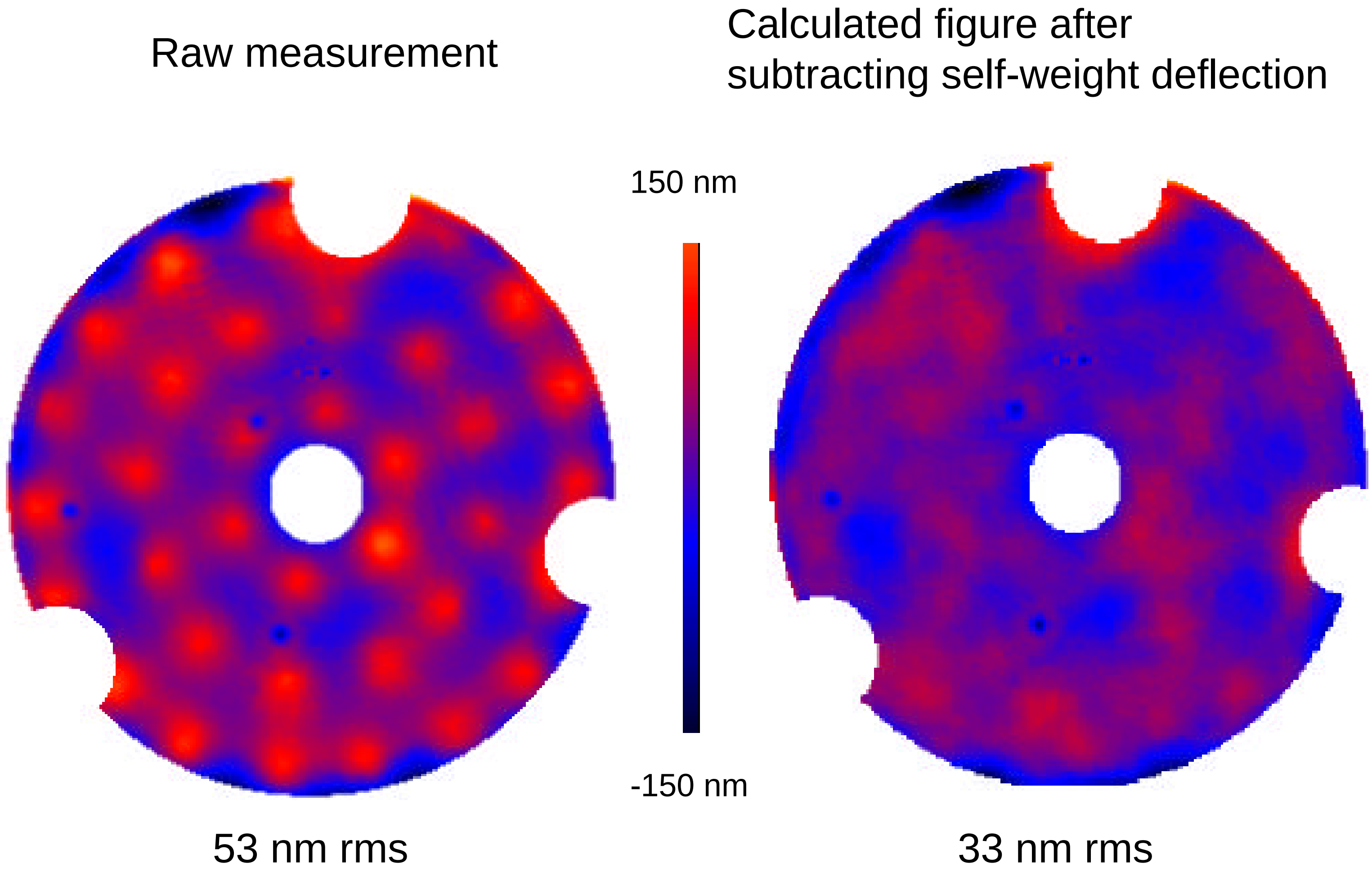
Baseline Approach: New Focus Picomotor

- split nut, 80 pitch screw
- piezo drive translates nut halves to advance screw
- “Flyback” leaves screw advanced by inertia
- 1 cycle advances screw 30 nm (current production)
- zero hold power
- very low dissipation when moved
- mass 40 g (current commercial production)
- 2 wire drive, can be very thin (100 V pulse, almost no current)
- no electronics or power dissipation on primary structure

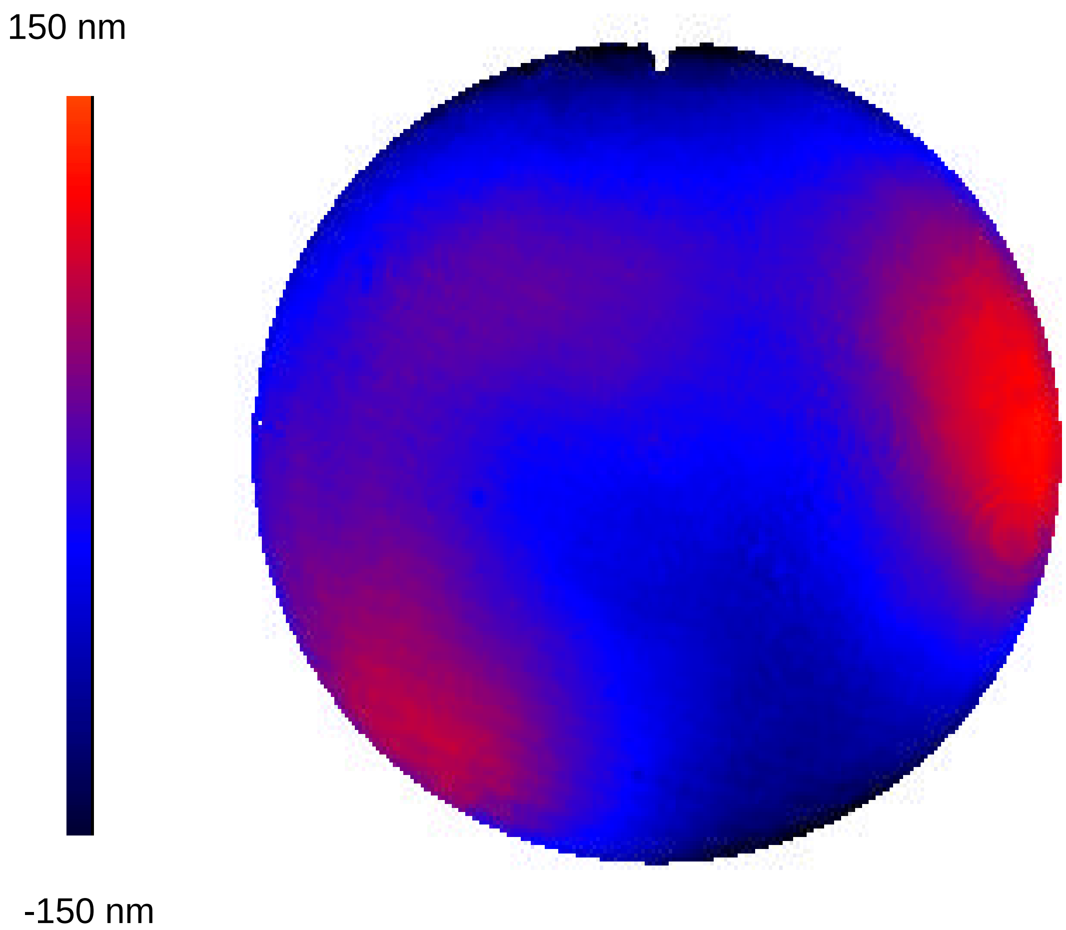


# Optical measurements of 53-cm prototype

After manually adjusting actuators to optimize the figure



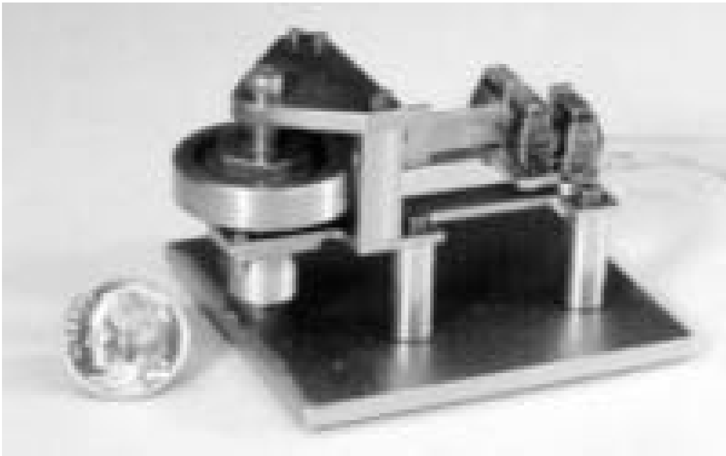
# Figure of shell while it was blocked down

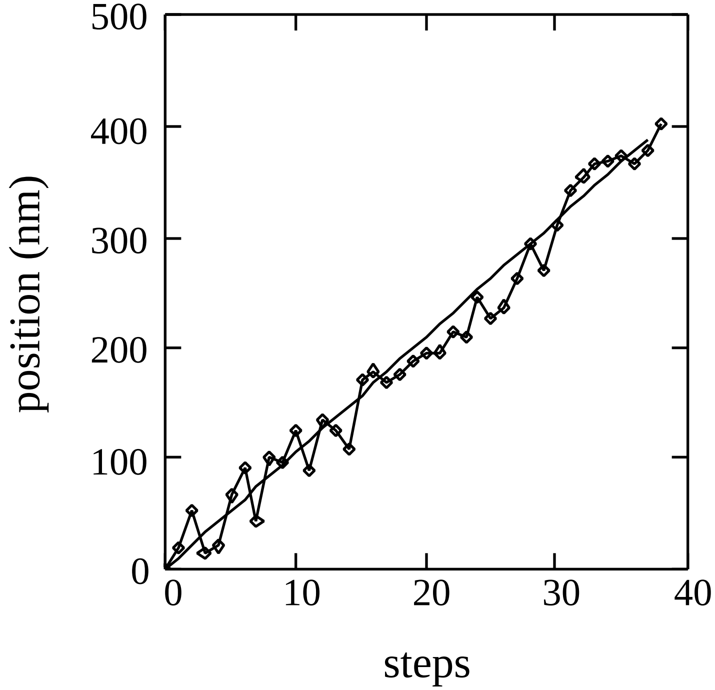



48 nm rms

# Cryogenic actuators

- Early prototype designed and built by ThermoTrex and U of A (uses proprietary ThermoTrex mechanism)
- Concept demonstrated, needs optimization and design for production
- Achieves 25 nm resolution at 77K
- Requires zero hold power
- 5 mm total travel
- total mass of 72 grams





# Demonstration of survival of 1-m glass membrane

- 2.2 mm shell, sagged to 4-m radius
- supported on 75 dummy actuators, roughly 100/m$^2$, giving ~400 Hz fundamental frequency
- aluminum backing plate
- Hit with 3 dB over Atlas IIAS load in Lockheed Martin's acoustic test facility
- Membrane survived shipping mishap as well as acoustic test
-

# Optimization of configuration

- Dominant effect is print through from the actuator forces required to correct warping in the membrane.
- Borosilicate glass chosen to minimize this effect
- 2 mm thick membrane, 50 actuators/$m^2$ with the load from each spread to 3 points on the glass chosen as optimal use of weight to achieve system mass density of 14 kg/$m^2$.
- Static gravity deflection of ~50 nm rms
- Attach to glass through flexures
- Optimize support for use, need temporary constraint for launch

# Analysis of figure errors due to support

- Shape errors in support structure or actuators are completely taken out with the closed loop system
- Actuators must apply some force to the membrane to correct its shape

  CTE variations in the membrane will cause the surface to warp when cooled

  Temperature variations will cause the membrane to warp

  The surface will have residual fabrication errors from polishing and support

- Force applied by the actuators will cause local "bumps" that are calculated as

$$\delta_{rms} = 0.0012 \frac{q}{D} \left( \frac{A}{N} \right)^2$$

$D$ = modulus of rigidity $= E\, t^3/12(1-\nu^2)$

From Nelson, et al, Proc SPIE 332 (1982).

## Calculation of reaction pressure to hold membrane figure

If a region on the membrane expands, it pushes against the area around it and makes a “blister”

The relationship between pressure to contain his blister and the internal stress is calculated assuming static equilibrium

Reaction pressure $q = 2\, t\, \sigma / R$

## Calculation of figure error due to CTE, temperature variations

If edge of blister is unyielding, replace σ with E Δ(α T), unrealistic

Better model using Δ(α T) with sinusoidal or Gaussian spatial profile,
Used finite element modeling  empirically determine  σ ~ 0.36 E Δ(α T)

Use this to calculate figure due to support forces holding the correct global shape

$$\delta_{rms} = \frac{0.01(1-\nu^2)}{R\ t^2 \left(\frac{N}{A}\right)^2}\ \Delta(\alpha T)$$

## Interesting results from analysis

- These effects are independent of the spatial scale of the stress
- Using triangular load spreaders to distribute the force from each actuator to 3 points can improve the figure 9 x
- Another form of equation is

$$\delta_{rms} = \frac{0.01\left(1-\nu^2\right)\rho^2}{R\left(\frac{m}{A}\right)^2\left(\frac{N}{A}\right)^2}\,\Delta(\alpha T)$$

where $m/A$ is allotted mass per unit area of glass

Does not depend on E!!!!

Stiffer materials require more force per actuator to hold their shape, but have proportionally smaller bumps/unit force

Important parameters are density, CTE variations, and cryogenic CTE

## Optimize number of attachment points

Optimal use of mass (more actuators vs thicker membrane) found by differentiation

For a given mass allotment, the minimum surface irregularity is found when the

**mass of actuators + loadspreaders = membrane mass**

If this optimal condition is held, the rms figure goes as the mass allotment to the -4 power. (10% mass increase gives 40% figure improvement)

The mass of the support structure is independent

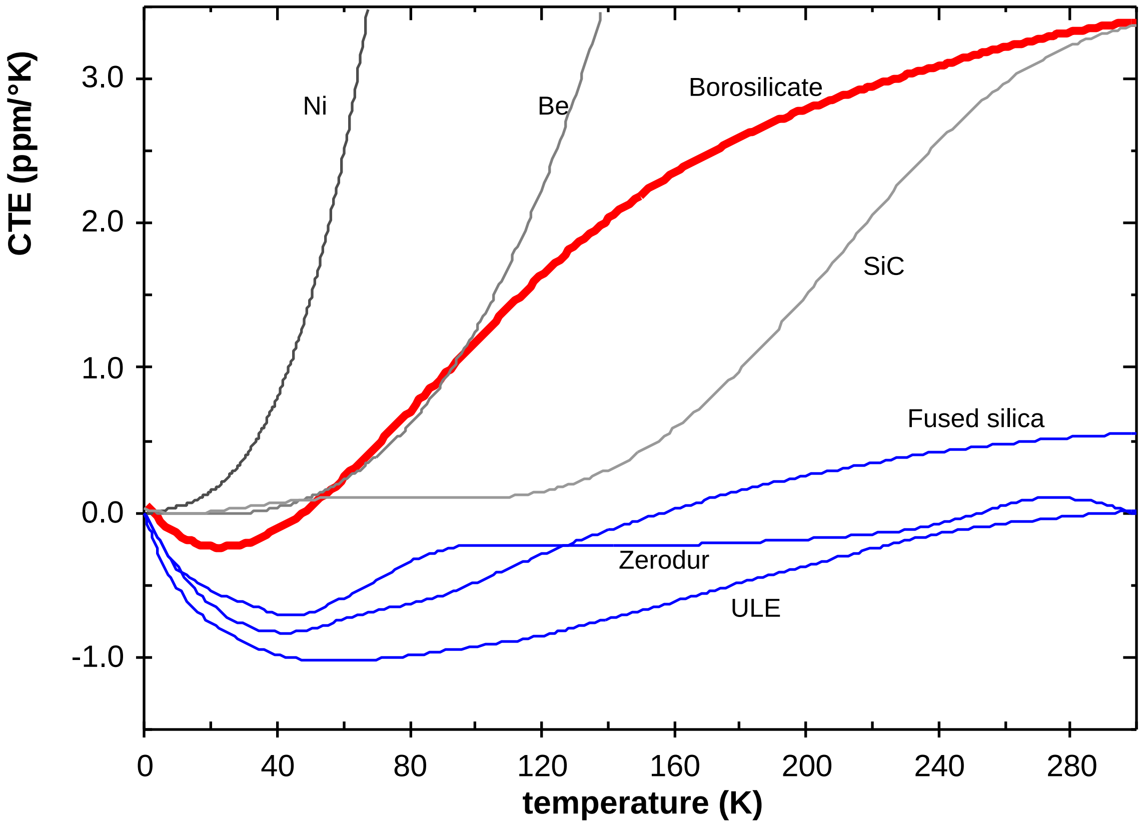
large scale $\Delta(\alpha T)$ of 1 ppm is corrected, leaving 4.2 nm rms bumps

small scale $\Delta(\alpha T)$ of 0.25 ppm of 2 nm rms is uncorrected

# Selection of material for membrane

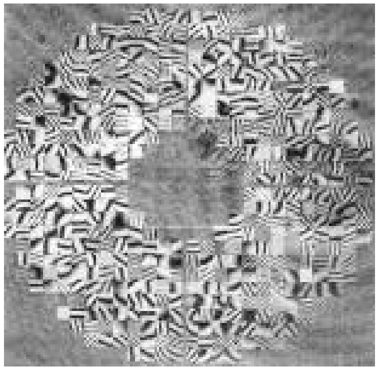
Need material that minimizes density, CTE at 40K, and CTE variations

Borosilicate glass is superior, and it is economical

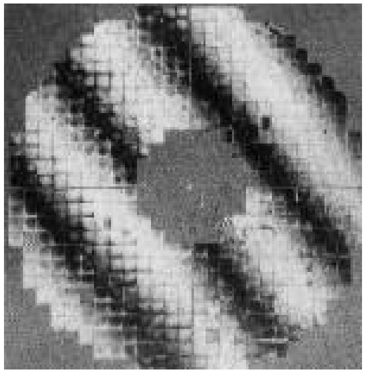


# Wavefront control system

- Wavefront sensors are under development (phase retrieval from images and interferometry with star light appear feasible)
- Make correction at primary, rather than inducing opposite distortion into a deformable mirror
- Close the loop using an on-board computer
- Adjust figure every few observations, or every few days, depending on stability.
- These types of systems are mature for ground based systems

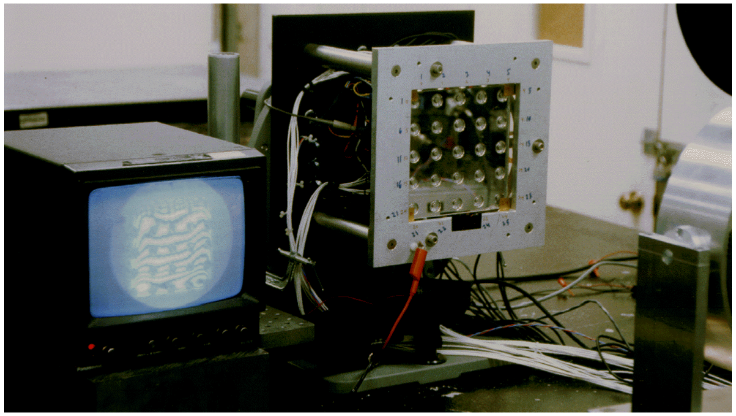


(a) initial state



(b) after adaptive correction.

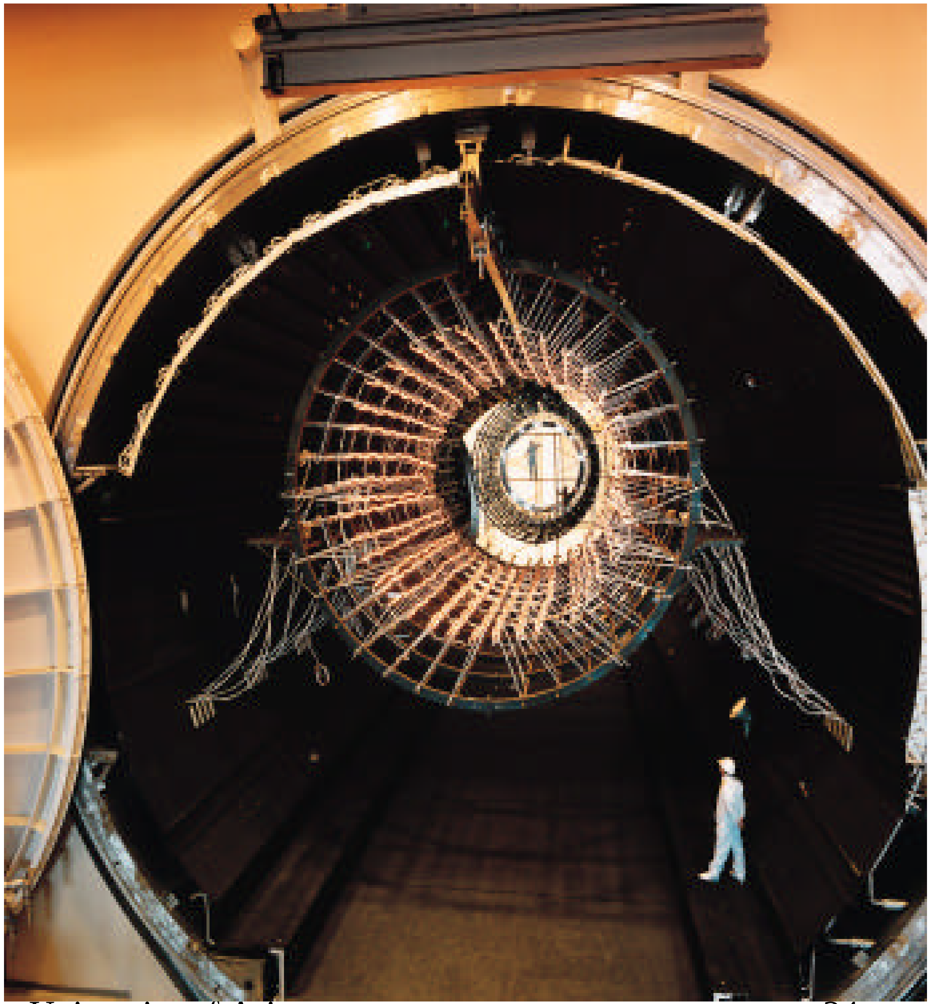
Segmented mirror built by TTC showing interference fringes for $\lambda$=351 nm.



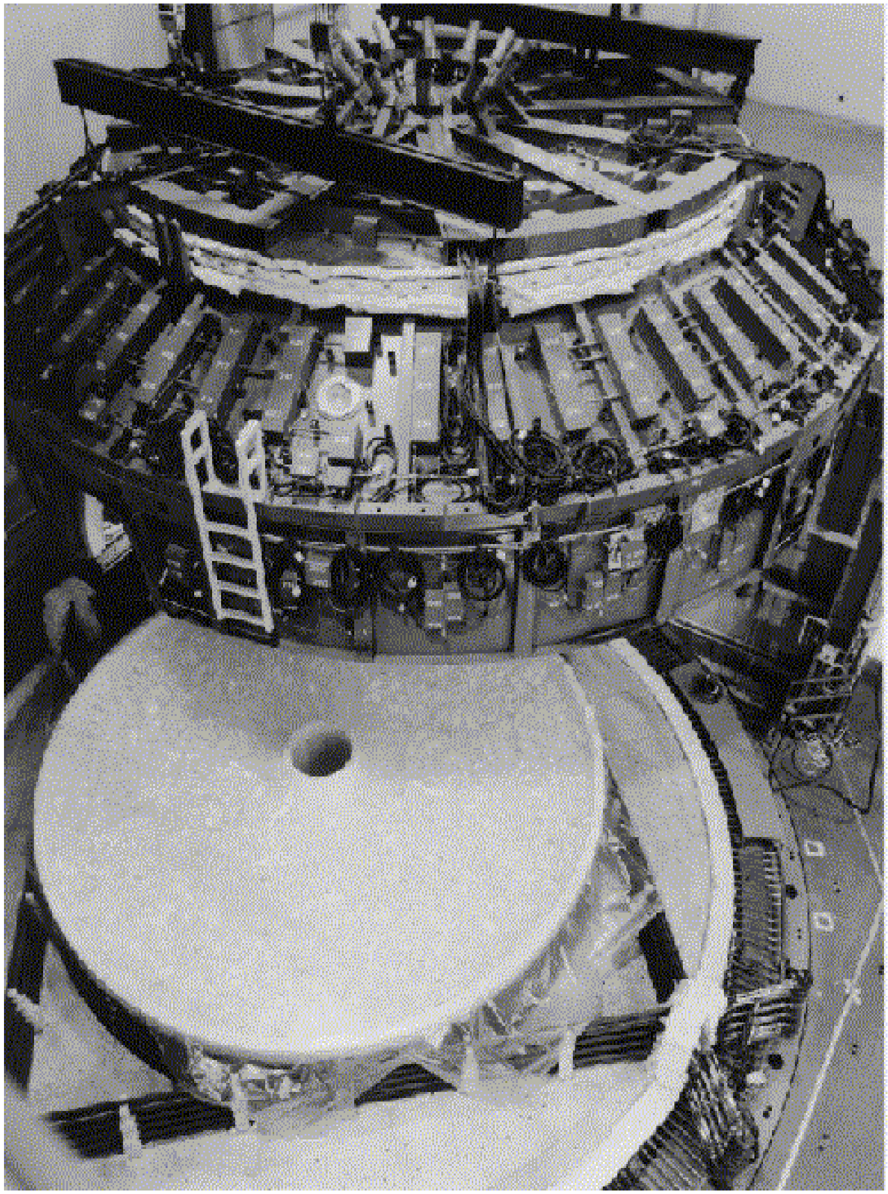
Prototype for the thin shell adaptive secondary mirror. This optic has a 2-mm membrane supported on 25 actuators with bandwidth > 100 Hz.

# Cryogenic demonstrations of the optics

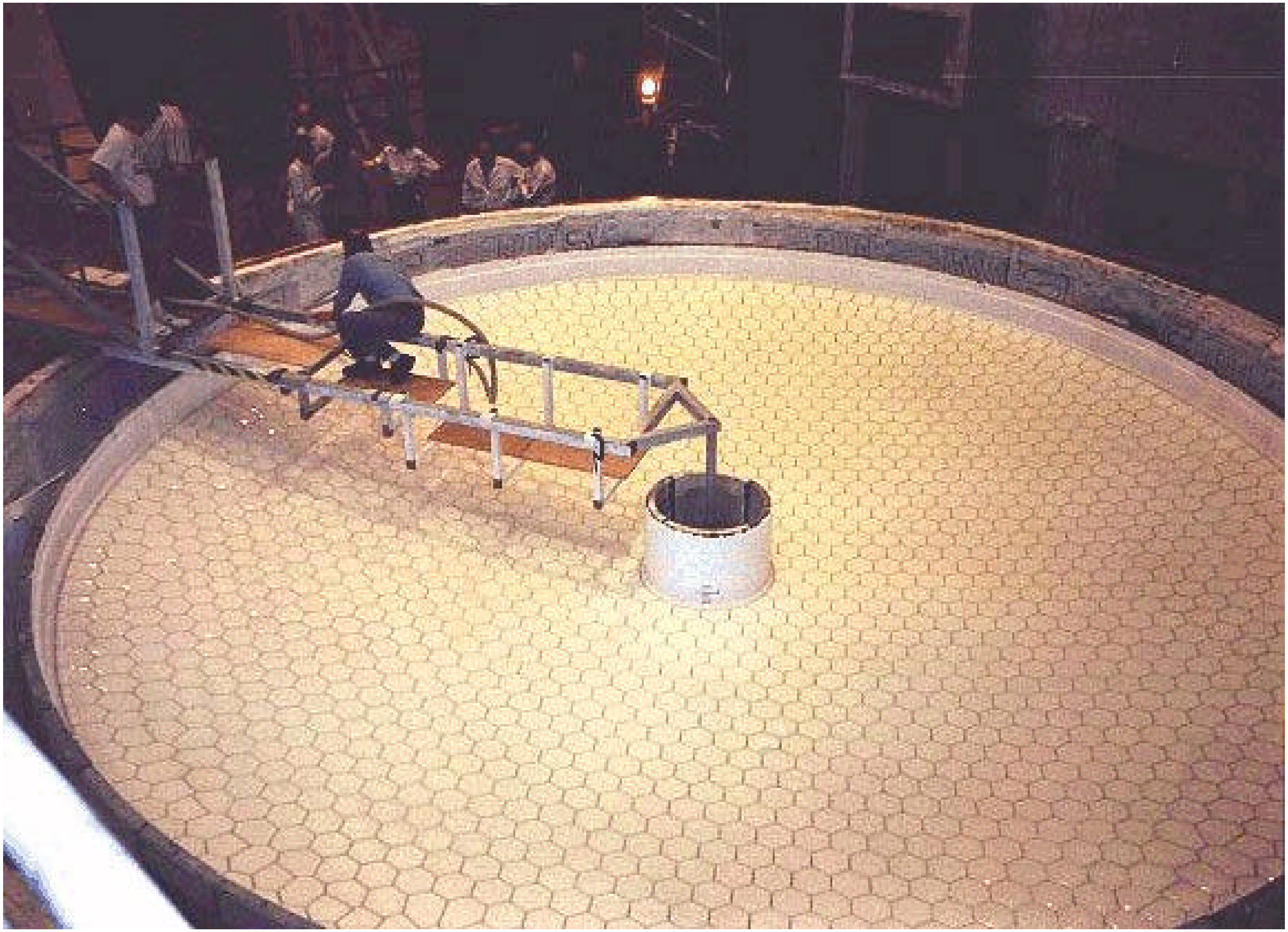
- Measurement of cryogenic material properties by Steve Jacobs at the University of Arizona
- Cryogenic measurement of deformations due to coupling to the glass at Lockheed Research Center in Palo Alto
- Interferometric measurement of the 2-m prototype at 40K at Lockheed Martin Sunnyvale facility ->



# Casting glass in 8-m spinning furnace

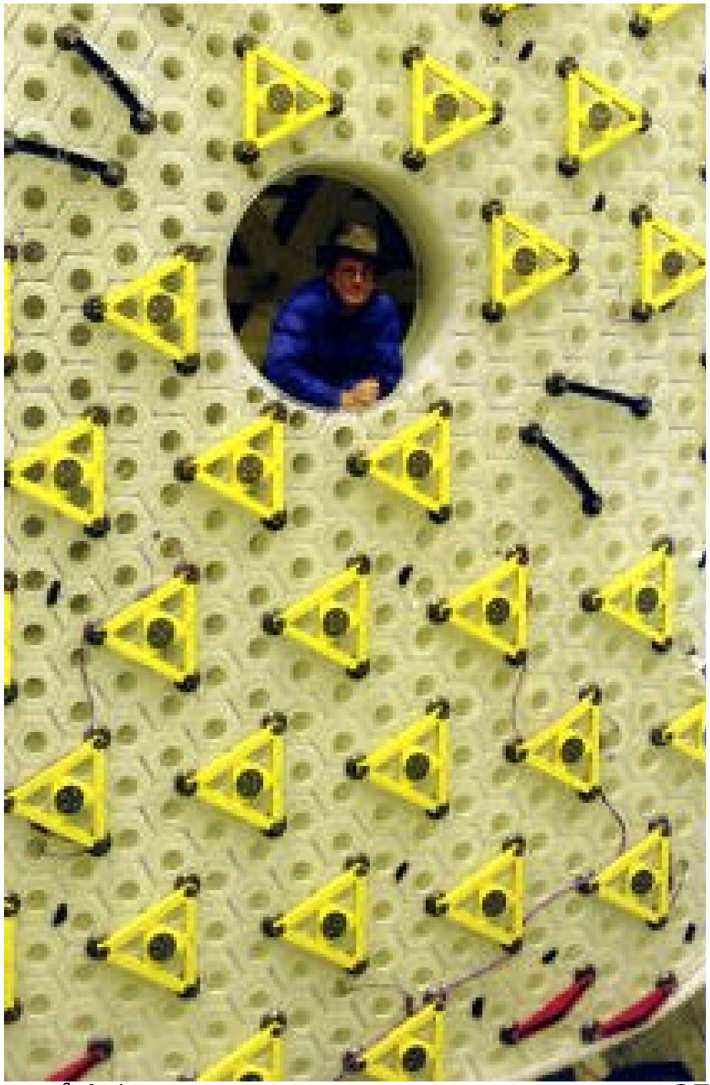


# 8.4-m f/1.1 primary mirror for the Large Binocular Telescope

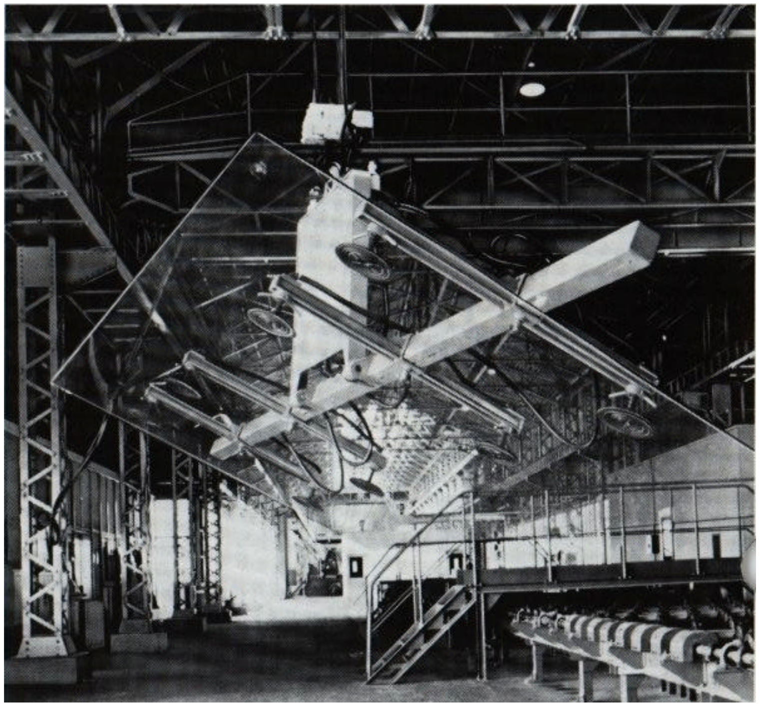


# Handling large optics

Thermally compensated load spreaders



Vacuum lifting fixtures



# Path to NGST flight mirror

*Most of the required technologies are fully developed!*

- Select and fully qualify material for membrane
- Engineer actuators for production that can be retracted if stuck
- Demonstrate interface to membrane that works at 40K
- Develop system to protect the shell during launch
- Develop accurate, high resolution stellar wavefront sensing
- 2-m demonstration of shell fabrication and cryogenic testing
- Figure out how to get it into space

  Develop capability to launch fully assembled 6-m telescope or
  Develop technology for assembling the mirror from segments